A STUDY ON THE EFFECT OF AUSTEMPERING TEMPERATURE, TIME AND COPPER ADDITION ON THE MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE IRON

A THESIS SUBMITTED
IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

Master of Technology
In
Metallurgical and Materials Engineering

Submitted By

Sandeep Kumar Sahoo

Roll No. 208 MM 102

Department of Metallurgical and Materials Engineering
National Institute of Technology, Rourkela-769008

May 2012

A STUDY ON THE EFFECT OF AUSTEMPERING TEMPERATURE, TIME AND COPPER ADDITION ON THE MECHANICAL PROPERTIES OF AUTEMPERED DUCTILE IRON

A THESIS SUBMITTED
IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

Master of Technology
In
Metallurgical and Materials Engineering

Submitted By
Sandeep Kumar Sahoo
Roll No. 208 MM 102

Under the guidance of

Prof. S. Sen
Dept. of Metallurgical & Materials Engg.
NIT, Rourkela

Prof. S.C. Patnaik
Dept. of Metallurgical & Materials Engg.
I.G.I.T, Sarang

DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

CERTIFICATE

This is to certify that the thesis entitled ***"A Study on the Effect of Austempering Temperature, Time and Copper Addition on the Mechanical Properties of Austempered Ductile Iron "*** submitted by Mr. Sandeep Kumar Sahoo, Roll No. 208MM102 in partial fulfillment of the requirements for the award of Master of Technology in Metallurgical and Materials Engineering with specialization in "Metallurgical and Materials Engineering" at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under our supervision and guidance. To the best of our knowledge, the matter embedded in the thesis has not been submitted to any other university/Institute for the award of any Degree.

Supervisor
Prof. S. Sen
Met. & Mat. Engg.
National Institute of Technology,
Rourkela-769008

Co-Supervisor
Prof. S. C.Patnaik
Head of the Deptt.
Met. & Mat. Engg.
I.G.I.T, Sarang, Dhenkanal-759146

Acknowledgement

I take this opportunity to express my deep regards and sincere gratitude to my guide **Prof**. **Sudipta Sen,** Deptt. Met & Mat Engg., NIT, Rourkela for his valuable guidance, untiring efforts and meticulous attention at all stages during my course of work.

I would also like to convey my deep regards to my co-guide **Dr. S. C. Patnaik,** Prof. & Head, Met & Mat Engg., I.G.I.T, Sarang for his patience, constant motivation and regular monitoring of the work and inputs, for which this work has come to fruition.

I express my gratitude to **Prof. B. C. Ray,** Head of the Department for providing me the necessary facilities in the department.

I am thankful to **Prof. B. B. Verma** for his invaluable advice, constant help, encouragement and inspiration.

I am also thankful to all the deptt. staff of both the institute for their co-operation in experimental work.

Sandeep Kumar Sahoo

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

The most rapidly growing area of cast technology is that of ADI or Austempered Ductile Iron. ADI is a heat treated Ductile Iron or S.G. iron with a unique micro-structure: Ausferrite which consists of high carbon Austenite and Bainitic ferrite with graphite nodules dispersed in it. This unique microstructure yields excellent properties: high strength, toughness, good wear resistance, good machinability and all that at low cost. The use of this type of cast iron as an engineering material has been increasing day by day since its discovery. These properties can be achieved upon adequate heat treatment which yields optimum microstructure for a given chemical composition. But this type of treatment is bit tricky, since it requires controlled heating and isothermal holding of the material.

In this work an investigation has been conducted on ductile iron with and without Copper additions and austempered in a range of time and temperature. An attempt has been made to study the effect of austempering time and temperature and the influence of copper addition on the mechanical properties of ADI. The tensile strength was found to increase with decreasing austempering temperature with maximum tensile strength seen in samples austempered at lower temperatures, 250°C and shorter times. Maximum ductility was obtained after austempering for 1.5 hours. An increase in the ductility of ADI was found on copper addition. Hardness of both the samples was found to be decreasing with increasing austempering time and temperature, and toughness of ADI was seen to be increasing with increasing time and temperature and was more prominent in case of ADI samples with copper.

Key words: ADI, austempering, ausferrite, elongation, toughness

Chapter 1

Introduction

1. Introduction

The material which offers the design engineer the best combination of low cost, design flexibility, good machinability, high strength to weight ratio & good toughness, wear resistance is Austempered Ductile Iron (ADI) [1]. Austempered Ductile Irons are an interesting class of materials because of their unique microstructure and interesting properties. When subjected to austempering treatment ductile iron transforms to a microstructure consisting of ferrite and stabilized austenite rather than ferrite and carbide as in austempered steels. Because of the presence of stabilized austenite, ADI exhibits excellent combination of strength and ductility, together with good fatigue and wear properties [2,3]. Compared to the conventional grades of Ductile Iron, ADI delivers twice the strength for a given level of ductility in the form of elongation. But achieving excellent mechanical properties of the ADI material is not an easy task as they depend on austempered microstructure which is a function of its processing window. The optimum combination of high carbon austenite and bainitic ferrite of ADI makes it possible to compete against steel forgings and other engineering alloys in terms of mechanical properties, physical properties, weight saving and all that at low cost. ADI offers superior combination of properties because it can be cast like any other member of the Ductile Iron family, thus offering all the production advantages of a conventional Ductile Iron casting. The ductile Iron casting is subsequently subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron and forged steel. Due to its vast area of applications, extensive works are being carried out now-a-days to study the processing and characterization of this material.

Chapter 2

Literature Review

- Cast Iron
- Ductile Cast Iron
    - Heat Treatment of Ductile Iron
        - Austenitizing the Ductile Cast Iron
        - Austempering of Ductile Cast Iron
- Austempered Ductile Cast Iron (ADI)
    - Microstructure of ADI
    - Graphite in ADI
    - Copper in ADI
    - Properties of ADI compared to steel and cast iron
    - Applications of ADI
- Aim of the work

2. Literature Review

2.1. Cast Iron

ADI stands for Austempered Ductile Iron and comes under the cast iron family. Cast iron is the eutectiferrous Iron-Carbon alloy i.e. eutectic reaction takes place during its solidification. As the liquidus line of iron-carbon diagram moves downward till the eutectic composition melting of cast iron becomes easier. The ductility of cast iron is very low. These alloys cannot be mechanically worked at room temperature. Most of the cast irons are not malleable at any temperature. However, they melt readily and they can be cast into complicated shapes. Then they are usually machined to final dimensions. Since casting is the only suitable process for shaping these alloys therefore they are called cast irons. Plain Iron carbon alloys with carbon up to 2.11 wt % in iron are called steels and beyond that the alloys are called cast irons. The cast irons are brittle. Theoretically the carbon content of cast iron can lie in between 2.11 % to 6.67 %. As higher carbon contents tend to make the cast iron more brittle, the industrial cast irons have carbon normally in the range of 2.11% to 4.0% [2, 4].

Cast iron is very similar in structure and composition to blast furnace pig iron, except that pig iron contains mechanically held slag and large amount of gases. The pig iron finds application to cast mould for steel-ingot, and therefore is called cast iron. Cast irons are essentially re melted pig iron, the composition of which has undergone some adjustments during melting process, by mixing it with cast iron scrap, steel-scrap etc. The melting unit may be cupola, electric arc or induction furnace etc.

The term “Cast iron” refers not to a single material, but to a family of materials whose major constituent is iron with important amount of carbon and silicon. Cast irons are natural composite materials whose properties are determined by their microstructures- the stable and meta-stable phases formed during solidification or subsequent heat treatment [5]. The best method to classify cast iron is the metallographic structure. The several variables which lead to the different types of cast irons are as given under.

- Carbon content

- Alloying element
- Impurity content
- Cooling rate during and after freezing
- Heat treatment after casting

These variables influence the form and shape of the carbon. Carbon in cast iron can be present in two forms:

- Combined form (Metastable)- cementite (Fe_3C) as in white cast iron
- Free form (stable)- graphite as in gray cast iron

As cementite is very brittle it makes white cast iron brittle and finds limited applications where only wear resistance is of importance. But graphite is soft; again if in spheroidal form as in case of ductile iron it increases the mechanical properties. But formation of graphite in cast iron is not spontaneous as that of Fe_3C metastable phase. Kinetically it is easier to produce Fe_3C (6.67 wt %C) rather than graphite (100 wt %C). So it is needed to adjust the processing window and use of graphitisers like Si, Ni and spherodisers like Mg, Ce for the formation of spheroidal graphite in cast iron [4].

The shape and distribution of the graphite will greatly influence the physical and mechanical properties of the cast iron. Based on the shape and form of the carbon in the cast iron and alloying additions the different types of cast irons are as follows:

- White cast iron
- Malleable cast iron
- Gray cast iron
- Ductile cast iron
- Alloy cast iron

Although the common cast irons are brittle and have lower strength than steels yet they are cheap and can be cast more readily. The cast irons also have other useful properties. Further, by proper alloying, good foundry control, and through appropriate heat treatment, the properties of cast iron may be varied over a wide range. Significant developments in foundry control have led to the production of huge tonnage of cast iron with consistent properties [5].

2.2. Ductile Cast Iron

Nodular Iron or Spherodised Graphite (SG) iron is known as Ductile Iron which was patented in 1948. After a decade of intensive development work, in the 1950's, ductile iron had a phenomenal increase in the use as an engineering material during the 1960's, and the rapid increase in commercial application continues today [4].

SG iron derives its name as it has graphite in the form of spheroid embedded in the steel matrix, normally of ferrite, or pearlite. And in the as-cast form, it exhibits measurable ductility. By contrast, neither white cast iron nor grey cast iron exhibits significant ductility. Nodular cast iron differs from malleable iron in the way that it is usually obtained as a result of solidification and not through heat treatment in the solid state. The spheroids in nodular iron are more rounded than the irregular temper carbon aggregates found in malleable cast iron.

The total carbon content of nodular cast iron is the same as in gray cast iron. Spheroidal graphite particles form during solidification due to the presence of small amount of certain alloying element. These nodules are produced by treating the molten alloy with magnesium, or cerium or a combination of two elements such as Ca, Ba, Li, and Zr causing spheroidal graphite to grow during solidification. Since these elements have a strong affinity for sulfur, the base iron alloy sulfur content must be below 0.015% for treatment to be effective. Ductile iron having a maximum of 10% pearlite in the as cast matrix is known as ferrite iron. This structure gives the maximum ductility, toughness and machinability.

A matrix structure which is largely pearlite can be produced as cast or by normalizing. Normalizing is carried out by air cooling from temperature of 870 to 900^{o}C. Pearlite ductile irons are stronger but less ductile than ferrite iron. A martensite matrix may be obtained by quenching in oil or water from 870 to 927^{o}C. The quenched structures are usually tempered after hardening to the desired strength and hardness level.

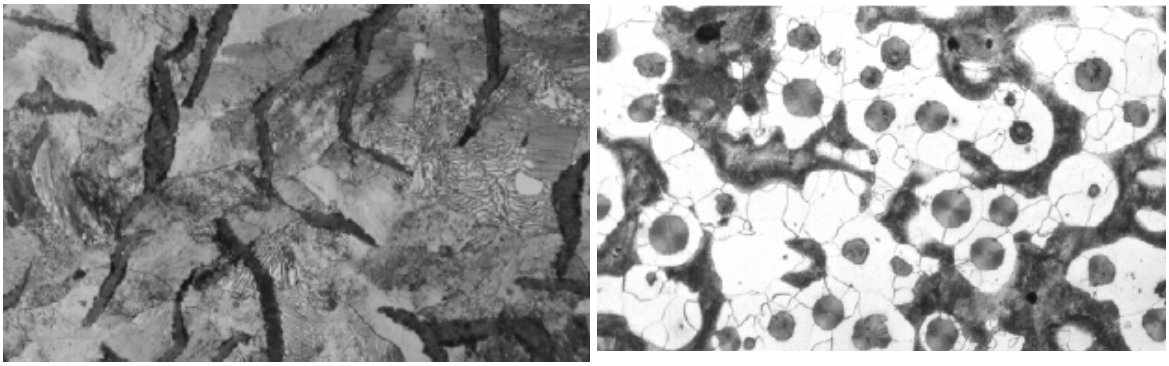
Austenite ductile iron is highly alloy type which retains their austenitic structure down to at least -60°C. These irons are used because of its high corrosion resistance and good creep properties at elevated temperature.

It was found that by adding magnesium to the melt before pouring caused the graphite to form nodules rather than flakes. This produced a new material with excellent tensile strength and ductility. With the addition of the mechanical properties of this material with the advantages already offered by cast iron led to it finding its way into almost every major area of engineering, and in many cases replacing existing steel castings or forgings due to achievable cost savings.

The matrix of ductile irons can be varied from a ferritic structure which is soft and ductile, through pearlitic structures which are harder and higher strength to a very hard, higher strength and comparatively tough tempered martensitic or bainitic structure. Thus, a wide range of combinations of strength and ductility can be achieved. The general grades of ductile iron commonly have ferritic, ferritic and pearlitic, or pearlitic structures.

The different grades are produced by controlling the matrix structure around the graphite either the as cast or by subsequent heat treatment processes. Only minor compositional differences exist among the regular grades, and these adjustments are made to promote the desired matrix microstructures which ultimately enhance their properties. Alloy addition may be made to help in controlling the matrix structure as-cast to provide response to heat treatment.

Experiments have shown that proper heat treatment methods can improve the properties of Cast Iron. And in some cases it may even overshadow the advantages of steel over Cast Iron. A large number of researchers are working on austempered Cast Iron which shows very good combination of properties.



(a) Flakes in Gray Cast Iron (b) Spheroids in SG Iron

Figure 2.1 The graphite in different forms in the microstructure of cast iron

2.2.1. Heat Treatment of Ductile Iron

Nodular cast irons are primarily heat treated to create matrix microstructures and associated mechanical properties not readily obtained in the as-cast condition. As-cast matrix microstructures usually consist of ferrite or pearlite or combinations of both, depending on cast size and composition. The normalizing, hardening, and austempering heat treatment, involve austenitization, followed by controlled cooling or isothermal reaction, or a combination of the two. The heat-treatments can produce a variety of microstructures and greatly improve the mechanical properties of ductile cast iron. These microstructures can be separated into two broad classes:

- Those in which the matrix phase is the thermodynamically stable body-centered cubic, ferrite structure
- Those with a matrix phase that is a meta-stable face-centered cubic, austenite structure. The former are usually generated by the annealing, normalizing and tempering, or quenching and tempering processes.

The latter are generated by austempering, an isothermal reaction process resulting in a product called austempered ductile iron (ADI).

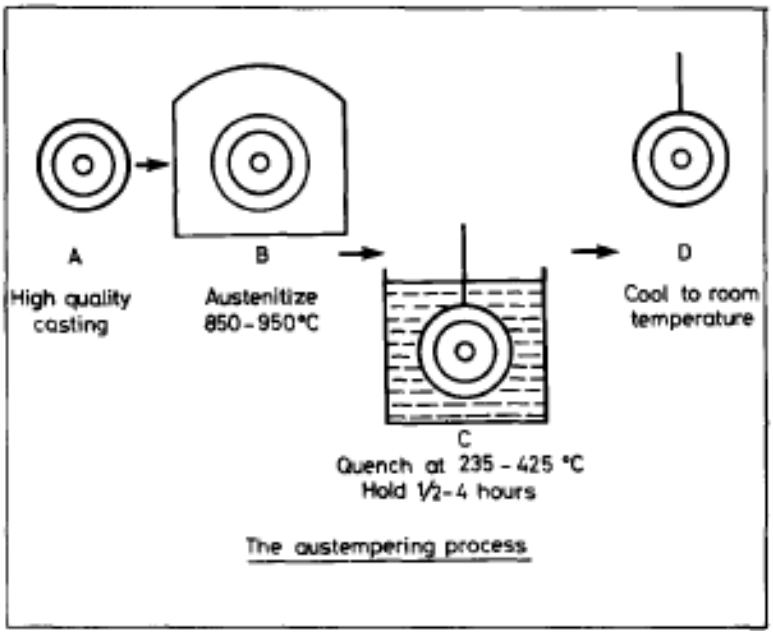


Figure: 2.2: The austempering process [1]

Other heat treatments in common industrial practice include stress-relief annealing and selective surface heat treatment. Stress-relief annealing does not involve major micro-structural transformations. And selective surface treatment processes like flame and induction surface hardening involve micro-structural transformations but only in selectively controlled parts of the casting [6].

2.2.1.1. Austenitizing the Ductile Cast Iron

The objective of austenitizing is to produce an austenitic matrix with as uniform carbon content as possible prior to thermal processing. For a typical ductile cast iron, it must be heated above the upper critical temperature so that the austenitizing temperature is in two-phase (austenite and graphite) region. This temperature varies with alloy content. The austenite carbon content in equilibrium with graphite increases with an increase in austenitizing temperature. This ability to select (within limits) the carbon content of the austenite matrix makes austenitizing temperature control important in processes that depend on carbon in the matrix to drive a reaction. The hardenability or austemperability of Ductile Iron depends to a significant degree on matrix carbon content. The composition, the original microstructure, and the section size of the Ductile Iron determine the time required for austenitizing.

A typical Iron-Carbon diagram with 2% Si content shows as austenitizing temperature increases, so does the matrix carbon content. The matrix carbon content also depends on type and amount of alloying element present and their location in the matrix. The most important determinant of matrix carbon content in ductile irons is the silicon content. As Silicon content in ductile iron increases for a given austenitizing temperature, the carbon content in the matrix decreases [7].

2.2.1.2. Austempering of Ductile Cast Iron

For optimum strength and ductility of Ductile cast Iron an austempered structure of austenite and ferrite may be produced. The austempered matrix is responsible for a significantly better tensile strength along with good ductility than is possible with any other grade of ductile

cast iron. To obtain these desirable properties a careful attention to section size and the time-temperature exposure during austenitizing and austempering is required [7].

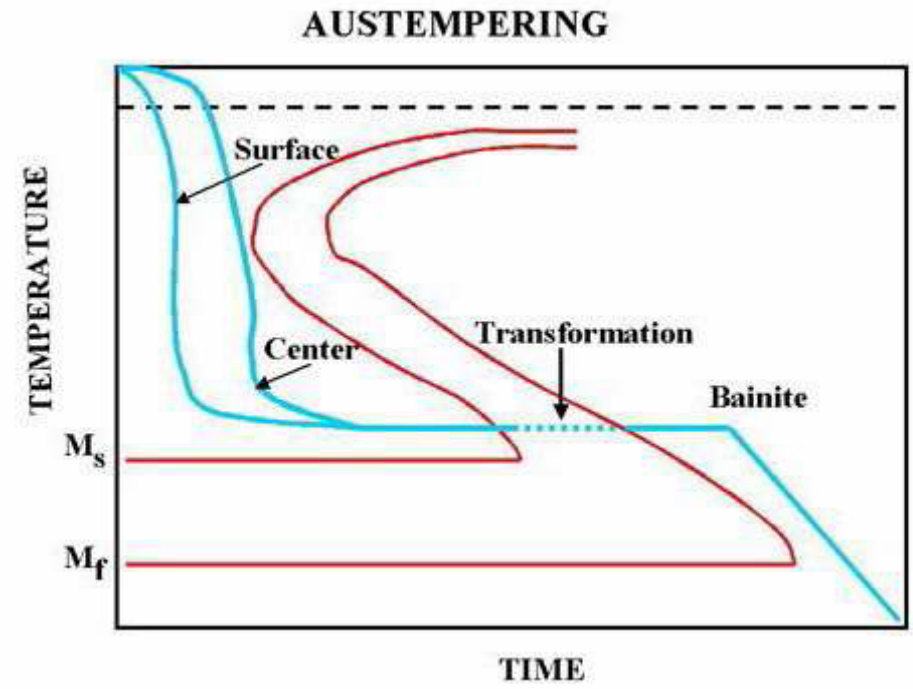


Figure 2.3 Time-Temp Curve of Bainite formation

The Austempering process consists of the following steps.

- Heating the Ductile Iron castings to austenitizing temperature.
- Holding at austenitizing temperature to dissolve carbon in austenite.
- Quenching quickly to austempering temperature to avoid pearlite formation.
- Holding at austempering temperature in molten salt bath for isothermal transformation to ausferrite.
- Air cooling to room temperature

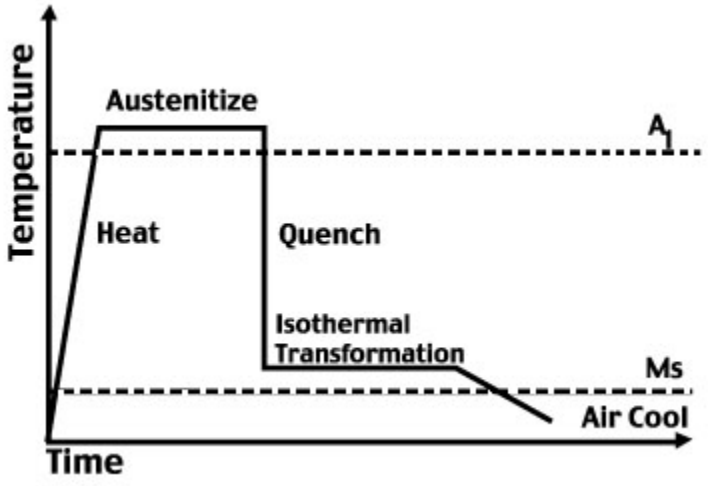


Figure 2.4 Austempering Procedure [8]

- The austenitizing times and temperatures (842° to 927° C) are controlled to ensure formation of fine grained austenite and uniform carbon content in the matrix. The precise temperature is grade dependant.

- Quench time must be controlled within a few seconds, to avoid formation of pearlite around the carbon nodules, which would reduce mechanical properties. Quench temperatures (235° to 400° C.) must be above the M_s temperature.

- In the austempering step which follows austenitizing, the temperature of the salt bath must also be closely controlled. The austempering time must also be controlled, to avoid over- or under-processing. By the end of this step, the desired ADI ausferrite structure has developed.

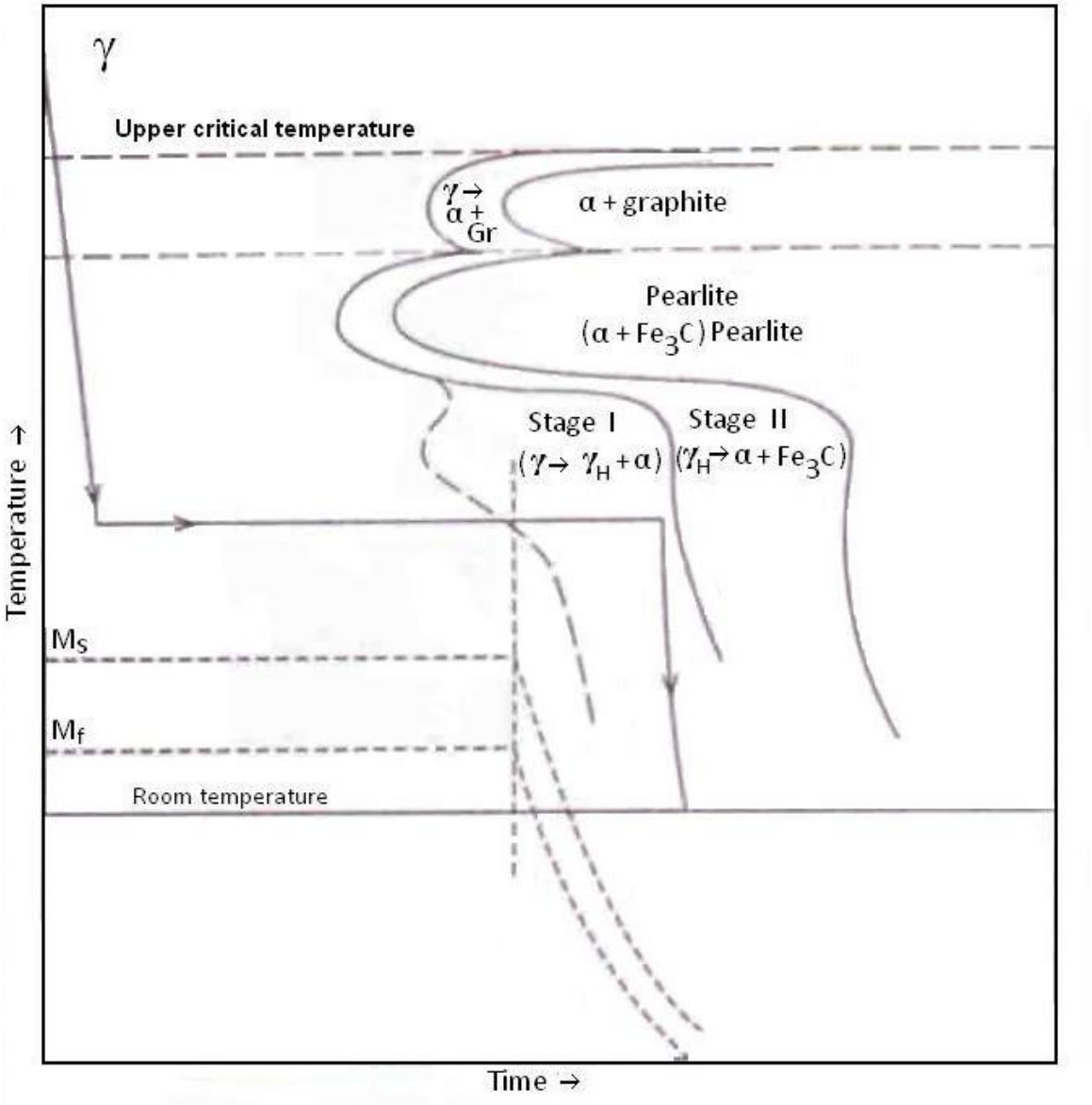


Figure 2.5 Isothermal transformation diagram of a processing sequence for austempering [7].

The isothermal transformation diagram for a ductile cast iron, together with a processing sequence depicting the production of ADI is shown in figure 2.5. In this process, austenitizing is followed by rapid quenching, usually in molten salt, to the bainitic temperature range for a time that allows the unique metastable carbon rich (~2%C) austenitic matrix (γ_H) to evolve simultaneously with nucleation and growth of plate like ferrite (α) or ferrite plus carbide, depending on the austempering temperature and time. This austempering reaction progresses to a point at which the entire matrix has been transformed to the metastable product of carbon rich

(~2%C) austenitic matrix (γ_H) with bainitic ferrite (stage-I in figure 2.5), and then the product is frozen by cooling to room temperature before the true bainitic ferrite plus carbide phase can appear (stage-II in figure 2.5). In ductile cast irons, the presence of 2-3% Si prevents the rapid formation of iron carbide (Fe_3C). Hence the carbon rejected during ferrite formation in first stage of the reaction retains in the austenite matrix, enriching it and stabilizing it thermally to prevent martensite formation upon subsequent cooling. The processing sequence in figure 2.5 shows that the austempering reaction is terminated before stage-II begins and it illustrates the decrease in the Martensitic start (M_s) and Martensitic finish (M_f) temperatures as γ_H forms in stage-I. Care should be taken to avoid formation of undesirable bainite as unlike steel, bainite in cast iron microstructures exhibits lower toughness and ductility [7].

2.3. Austempered Ductile Cast Iron (ADI)

ADI, the most recent addition to the Ductile Iron family, is a sub-group of Ductile Irons produced by giving conventional Ductile Iron a special austempering heat treatment. An optimum combination of high carbon austenite and bainitic ferrite (ausferrite) confers excellent mechanical properties to such cast irons on heat treatment making it possible to produce a family of ADIs. This in turn allows a wide range of applications with ADI competing favorably against steel forgings in terms of mechanical properties, manufacturing cost, physical properties and weight saving.

ADI is nearly twice as strong as pearlitic Ductile Iron and it still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength. Ductile iron castings are freely machinable before heat treatment. The casting properties are upgraded after machining through austempering treatment.

The bainitic transformation starts at the interfaces with the nucleation and growth of individual platelets of bainitic α-phase. The transformation progresses as a result of the formation of new individual platelets within clusters, which are called sheaves. These individual platelets are named ‘sub units’ or a sheaf. All subunits within a sheaf have the same crystallographic orientation. It is thought that sub units grow without diffusion, but the excess of carbon is quickly partitioned into the untransformed austenite [11].

It has been reported that two austenites with different carbon contents were found in the austempered ductile iron (ADI) matrix structure, but it is not clear how the change of carbon contents in both austenites affect the reaction [12]. The work of Kustuv and Taran [11] on ductile iron has shown that the volume fraction of austenite in the matrix in the isothermal transformation range between 400-250°C decreases (from 33 to 18%) with decrease of transformation temperature. The variation of carbon content and the c/a ratio in the bainitic α-phase against transformation temperature are given in figures 2.6 and 2.7 respectively.

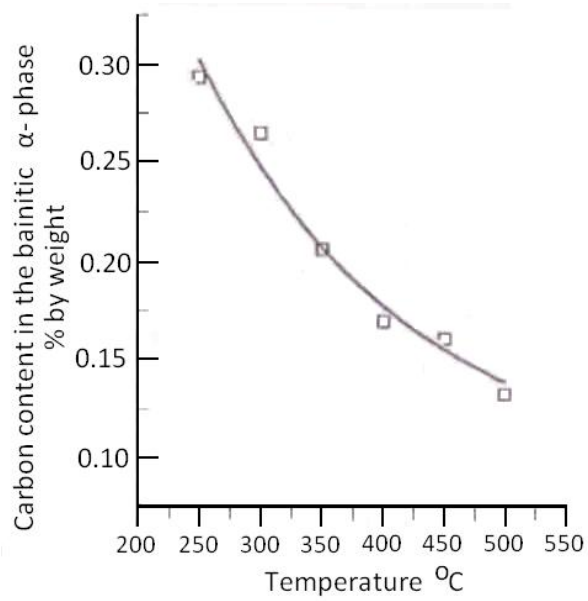


Figure 2.6 The carbon content in bainitic α-phase vs. the transformation temperature [11]

It is clear from figure 2.6 that the decrease of isothermal temperature within an interval of 500-250°C leads to a higher carbon amount trapped in the bainitic α-phase at the termination of isothermal transformation.

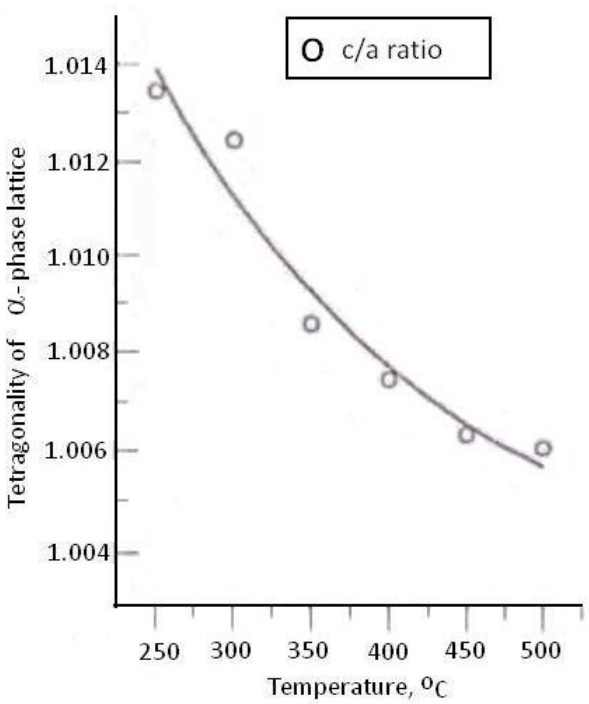


Figure 2.7 The tetragonality of bainitic α-phase lattice as a function of the transformation temperature [11]

The tetragonality (c/a ratio) in the bainitic α-phase is found to decrease with increasing temperature.

Different alloying elements have their individual effect and combinations of these alloying elements are selected for their effect on different properties of ADI like hardenability, elongation, toughness, tensile strength, hardness etc. by stabilizing different phases and transformation behavior. Table 2.1 summarizes the effects of various alloying elements on the austempering behavior of ADI.

Table 2.1 Effects of various alloying elements on the austempering behavior of austempered ductile iron ADI [7].

Element	Alloying effects
Carbon	Increasing in the range 3-4% increases the tensile strength but has negligible effect on elongation and hardness. Carbon should be controlled within the range 3.6-3.8%.

Silicon	Silicon in ADI promotes graphite formation, decreases the solubility of carbon in austenite, increases the eutectoid temperature and inhibits the formation of bainitic carbide. Increasing the silicon content increases the impact strength of ADI and lowers the ductile-brittle transition temperature. Silicon should be within the range 2.4-2.8%.
Manganese	Manganese can be both a beneficial and harmful element. It strongly increases hardenability, but during solidification it segregates to cell boundaries where it forms carbide and retards the austempering reaction. To improve properties and reduce the sensitivity of ADI to section size and nodule count, it is advisable to restrict the manganese level in ADI to less than 0.3%.
Copper	Up to 0.8% Cu may be added to ADI to increase hardenability. Copper has no significant effect on tensile properties but increases ductility at austempering temperatures below 350°C.
Nickel	Up to 2% Ni may be used to increase the hardenability of ADI. For austempering temperatures below 350°C nickel reduces tensile strength slightly but increases ductility and fracture toughness.
Molybdenum	Molybdenum is the most potent hardenability agent in ADI and may be required in heavy-section castings to prevent the formation of pearlite. However, both tensile strength and ductility decreases as the molybdenum content is increased beyond that required for hardenability. The level of molybdenum should be restricted to not more than 0.2% in heavy-section castings.

2.3.1. Microstructure of ADI

ADI is a heat treated Ductile Iron with a unique micro-structure consisting of Ausferrite which consists of high carbon Austenite and Bainitic ferrite with graphite nodules dispersed in it. ADI is a ductile iron that has been heat treated by the austempering process to make it tougher than regular ductile iron of half the strength. ADI is comparable in strength to heat treated wrought steels, has exceptional wear and fatigue resistance and has the ability to be work hardened. As the carbon rich austenite phase is stable in Austempered Ductile Iron it enhances

the bulk properties. Furthermore, while the austenite is thermodynamically stable, it can undergo a strain-induced transformation when locally stressed, producing islands of hard martensite that enhance wear properties. This behaviour contrasts with that of the metastable austenite retained in steels, which can transform to brittle martensite [9].

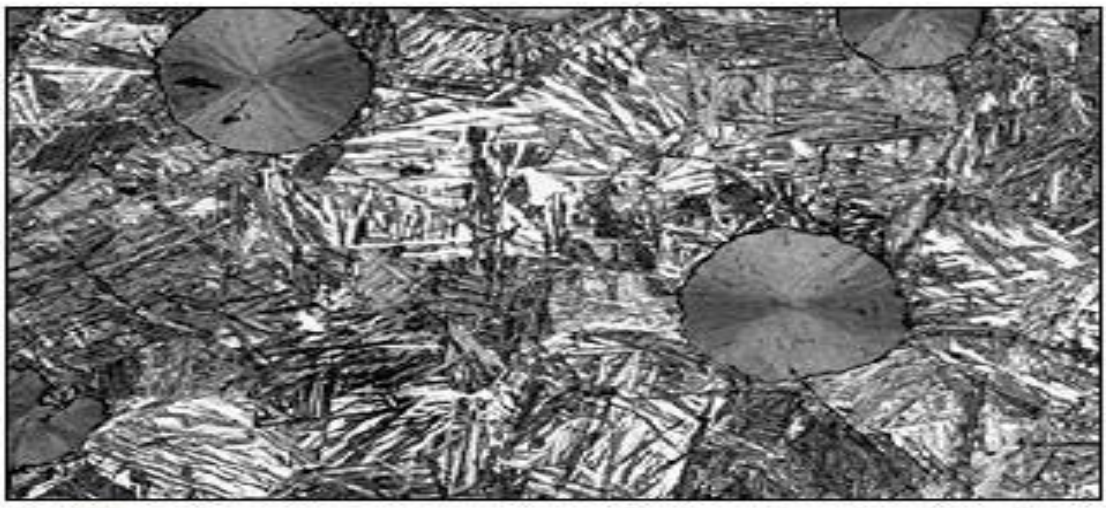
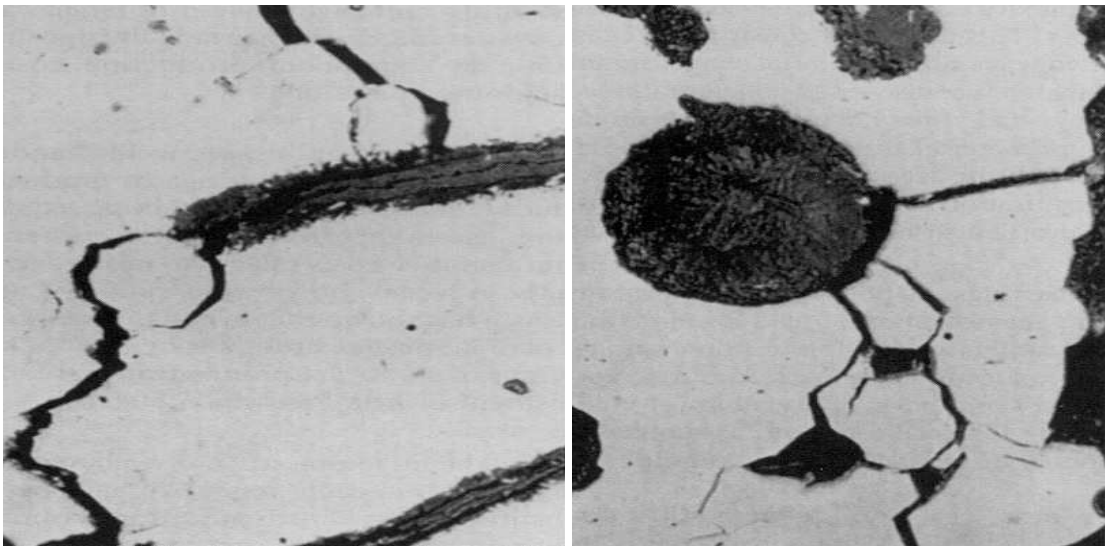


Figure 2.8 ADI Microstructure consists of acicular ferrite in high carbon austenite matrix called Ausferrite [10]

2.3.2. Graphite in ADI

Graphite is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of cast irons. The compact spheroid interrupts the continuity of matrix much less than graphite flake and this results in higher strength and toughness compared with a similar structure of gray cast iron. Figures 2.9 (a) and (b) show that graphite flakes act like cracks in the iron matrix, while graphite spheroids act like “crack arresters", giving the respective irons dramatically different mechanical properties [5].



(a) (b)

Figure 2.9 Different forms of graphite

In iron-carbon alloys, though graphite is more stable phase than cementite but kinetically, it is easier to produce cementite than graphite. When graphite forms directly from the liquid, it is called primary graphitization, but when the graphite forms from the dissociation of cementite, it is called second stage graphitization. The formation of graphite from liquid takes place in a narrow range of temperature interval (1153-1147°C for plain carbon) and also the formation of graphite from austenite (738-727°C) i.e. under the condition of small under cooling. This requires the alloy to be cooled slowly.

Nucleation of graphite requires much more energy and large amount of diffusion of carbon to the nuclei and iron atoms away from it to get 100% carbon to segregate. So formation of graphite from liquid in pure iron-carbon alloy is almost a rare reaction, unless the factors for graphite formation are favorable. Commercial cast iron melt always contains fine particles of inclusion, even particles of graphite. Nucleation of graphite on some of these inclusions needs less energy than that required or nucleation of cementite and thus graphite crystal can be formed kinetically even at temperatures below 1147^{o}C.

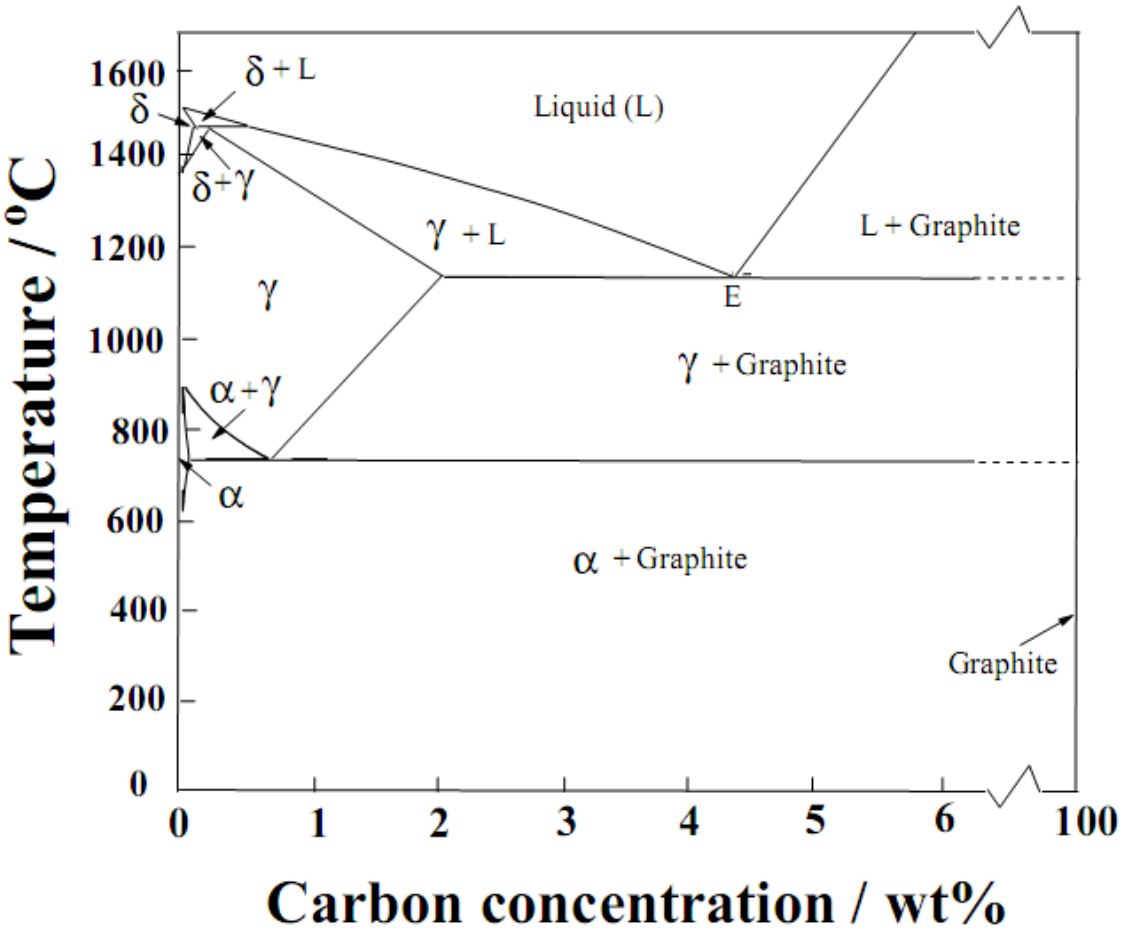


Figure 2.10 Iron Carbon Diagram

Graphite thus can form not only from liquid or austenite (738-727°C), the metastable cementite under favorable conditions, such as high temperatures can decompose to austenite + graphite (above738°C) or ferrite + graphite (below 738°C). The former is a faster process, but complete graphitization does not occur as 0.68% C remains dissolved in austenite, whereas the latter is the slower process, but complete graphitization occurs.

2.3.3. Copper in ADI

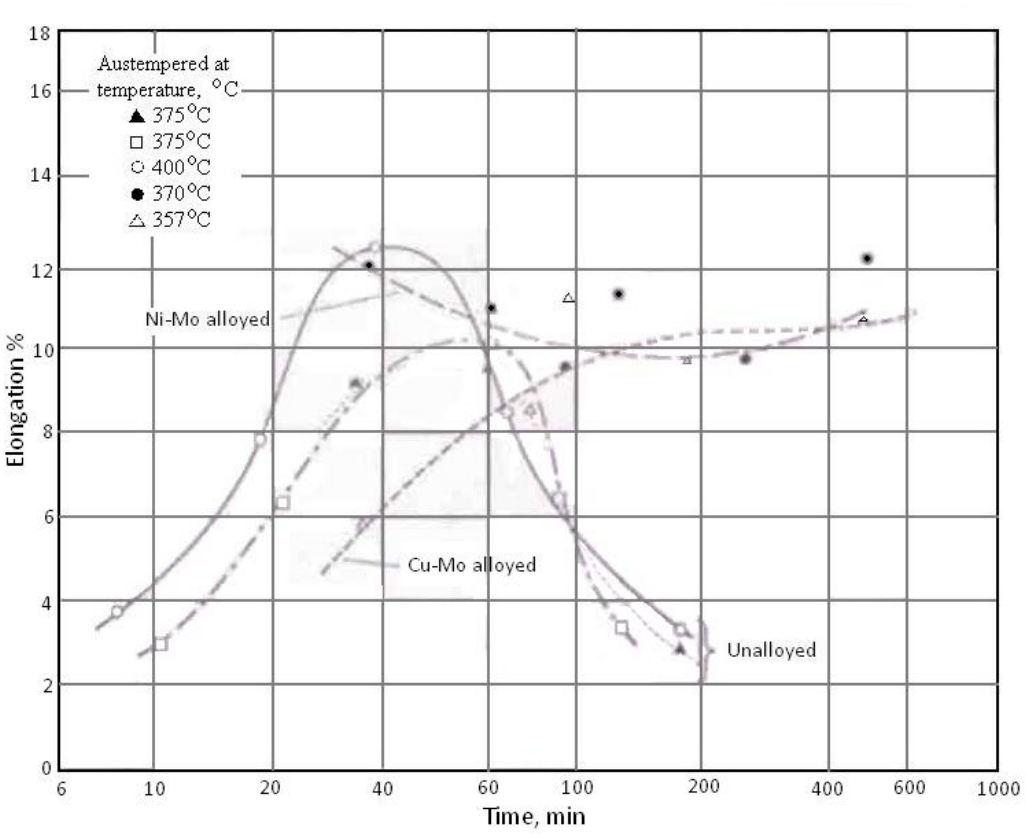


Figure 2.11 Elongation vs. austempering time for a group of ductile iron alloys [7]

Nickel and Copper segregate to graphite nodule sites and do not form detrimental carbides [7]. According to the experimental work of P. W. Shelton, A. A. Bonner [13] and Olivera Eric [14] alloying with copper increases elongation and impact energy but decreases the strength of ADI. According to their results it was seen that a straight forward addition of copper to a conventionally produced and heat treated ADI had not produced the well defined copper coated graphite nodules those were hoped for. In some cases the copper was associated with graphite nodules, but not as a thin film. There were also isolated pools of copper present in the microstructure comparable in size with graphite. The distribution and size of graphite spheroids was similar however for both the materials, with no evidence that the copper addition influenced either. Where there was porosity, a concave graphite surface or irregularity in the shape of the graphite nodule, the copper was often attracted to those features.

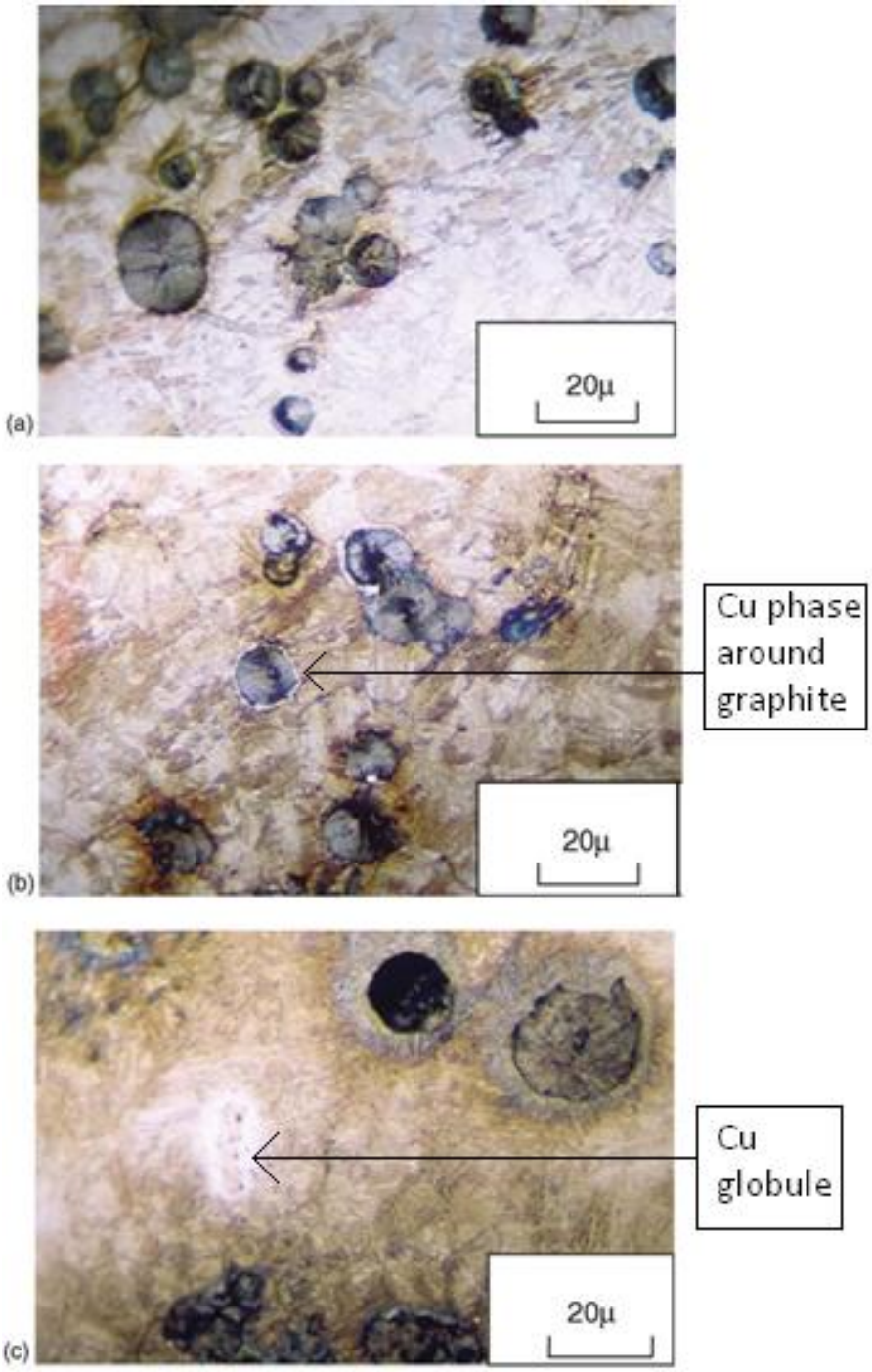


Figure 2.12 Austempered microstructures, etched in 2% nital. (a) Plain ADI austenitised at 940°C and austempered at 320°C. (b) Copper enriched ADI austenitised at 900°C and austempered at 290°C, showing nodules with copper-rich phase around all, or part of graphite nodule. (c) Copper enriched ADI austenitised at 940°C and austempered at 320°C showing a discrete copper globule, left of centre [14].

2.3.4. Properties of ADI compared to steel and cast iron

ADI is a proven cost-effective alternative to cast and forged steel and other members of its family as it offers the following advantages:

- Tensile Strength and Yield Strength of ADI are at least twice those of standard ductile irons.

- Fatigue Strength of ADI is typically 50% higher than that of standard ductile irons. It can be further increased by shot peening or fillet rolling. The lower hardness grades of ADI are suitable for structural applications [15].

- The excellent impact and fracture-toughness properties of ADI make it ideal for applications such as ground-engaging tools**.**

- ADI weighs only 2.4 times more than aluminum and is 2.3 times stiffer. ADI is also 10% less dense than steel. Therefore, the relative weight per unit of yield strength of ADI when compared with that of various aluminums and steels, it is easy to see the engineering and design advantages inherent in ADI [15].

- The higher hardness grades of ADI have excellent wear characteristics. Unlike case-hardened materials, typically the ADI is uniformly hardened throughout the part. Also, ADI work-hardens when stressed. This produces a thin surface of very hard martensite where wear resistance is most needed.

- ADI is usually 15% to 20% less costly than steel forgings or castings. It is the most economical way of obtaining tensile, yield, or fatigue strength. ADI often competes favorably with heat-treated and alloy steels for heavy-duty applications where reliability is crucial. It is a useful upgrade from standard grades of ductile iron. In some cases it replaces manganese steel and nickel-chrome iron. Because of ADI's high strength-to-

weight ratio, it has even replaced aluminum where the design allows reduced section sizes

- Nearness to net shape reduces machining costs.
- Tooling is less expensive with improved lead time when compared to forging dies.
- The amount of energy required to produce A.D.I. can be up to 50% less than steel casting and forging counterparts [15,16,17].

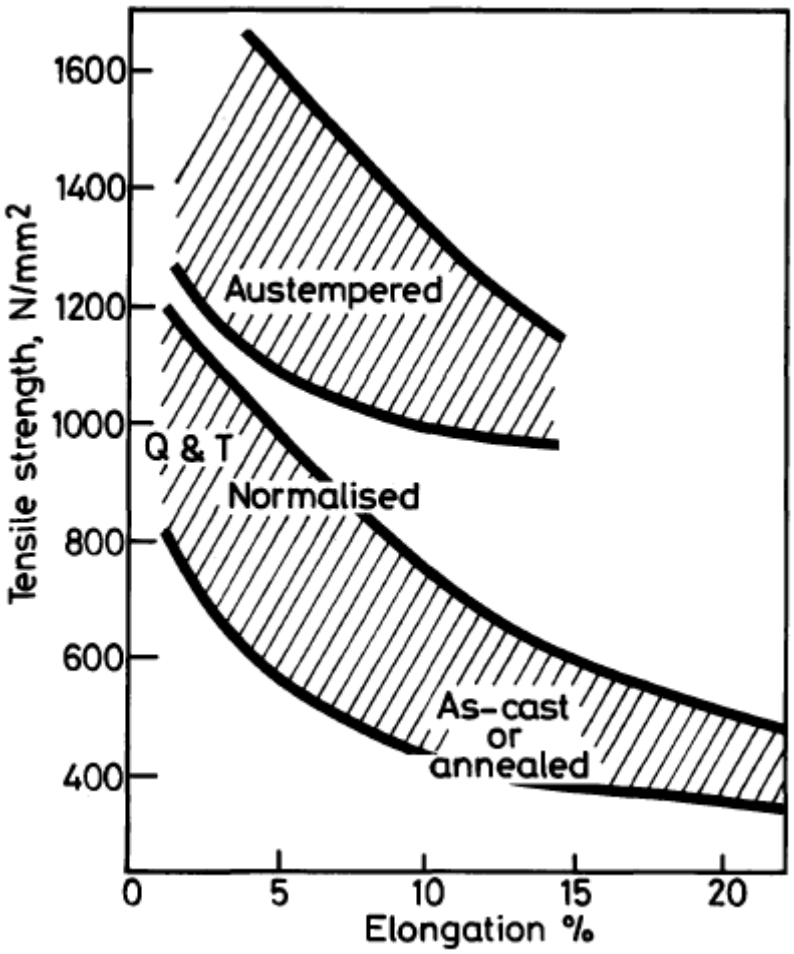


Figure 2.13 Tensile strengths and elongations in austempered ductile iron compared with other ductile irons [1].

2.3.5 Applications of ADI

Engineering applications of cast iron have been traditionally based upon gray (Flake graphite) irons providing a range of tensile strengths between about 150 N/mm^2 and 400 N/mm^2 with recommended design stresses in tensile applications of 0.25 x tensile strength. Despite their limited strength gray irons provided very useful combinations of properties, which have ensured there wide continuing use. In fact gray irons still account for nearly 70 % of all iron castings produced. In contrast ductile irons have tensile strengths ranging from 350 to 1500 N/mm^2 with good elongation and high toughness. They now account for about 25 % of iron casting production serving in safety critical applications where they have replaced steel casting, forging and fabrications with technical and cost advantage.

The main difference between ductile iron and gray iron is the morphology of graphite particles which take on a nodular or almost spherical form after suitable treatments are made to the melt. The major micro structural constituents of ductile iron are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbides are dispersed.

All of the advantages of Ductile Iron, described have contributed to the growth of this engineering material. The primary material that has been replaced is steel, in the form of castings, forgings and fabrications. However, Ductile Iron parts have also replaced gray iron, malleable iron and aluminium castings as well, proving that Ductile Iron is very cost effective.

Table 2.2 Partial list of castings produced in regular ductile iron [20]

(Casting weights from 10 grams to over 170 tons)

Automotive and Agricultural			
Axle housings	Body bolsters	Brake calipers	Brake cylinder
Camshafts	Clutch drums	Clutch plates	Connecting rods
Crankshafts	Cultivator parts	Cylinder bushings	Differential carrier
Differential case	Exhaust manifolds	Front wheel forks	Gears & pinions
Hitch brackets	Hubs	Motorcycle components	Pinion
Pinion flange	Planet carrier	Piston rings	Plow shares
Rocker arm	Ring gears	Spindles	Wheels
Steering housings	Tire molds	Truck cab mount	Steering knuckles
Yokes			
Other Transportation and Construction			
Anchors	Axle housings	Backhoe arms	Back. stabilizers
Bridge bearings	Cable coupler	Car journal boxes	Charge buckets
Chute plates	Conveyor frames	Covers	Crawler sprockets
Elevator buckets	Hand tools	Hoist drums	Idlers
Manhole covers	Mill heads	Pipe flanges	Propellers
Pole line hardware	Railroad wheels	Rollers	Runway grates
Swing pivots	Track crossovers	Tree grates	
General Engineering			
Actuating cams	Armature spiders	Barstock	Bearing housings
Die blocks	Boiler segments	Bolts	Brackets
Furnace grates	Cams	Clamp cylinders	Commutator drums
Bell cranks	Compressor bodies	Crusher hammers	Damper frames
Briquetting rams	Dredge sprockets	Forging dies	Frames and jigs
Crankcases	Gyratory crushers	Ingot molds	Heater coils
Hinges	Hydraulic valves	Insulator caps	Lawn mower parts
Lightening arresters	Machine frames	Mandrels	Meter components
Nuclear fuel container	Nuts	Oil manifolds	Overhead switch gear
Pile driver heads	Pipe forming dies	Pipe fittings	Pistons
Pressure pipe	Press roll bodies	Pump bodies	Ratchets
Resistance grids	Rocker brackets	Rolling mill rolls	Rope clamps
Rotors	Rubber molds	Sawmill beds	Scaffold fittings
Shafts	Shear frames	Spindles	Suspension brackets
Tank covers	Thread guides	Tunnel segments	Turbine casing
Turret heads	Valves	Vise frames	Wheels
Worm gears	Wood augers		

Austempered Ductile Iron is increasingly the material of choice as designers and engineers seek cost effective performance from their components and systems. In particular, manufacturers engaged in moving parts and safety critical items have benefited from increased strength, greater wear resistance, noise reduction and weight saving. [18,19].

ADI is now established in many major markets:
Table 2.3 List of castings produced in ADI [20]

Agricultural Equipment			
Digger points	Fertilizer knives	Corn grinder plates	Planter rachet gear
Pump cams	Slip clutch parts	Pump rotor	Track shoes
Tow hooks	Snow plow shoe	Link arm	Eye bolts
Jacking stand gear	Sprockets	Wear plates	Hitches
Sickle guards	Wheel hubs	Pavement breakers	Wear guides
Rollers	Steering shafts	Control arms	Plow & till points
Automotive and Truck			
Crankshafts	Connecting rods	Control arms	Engine mount
Diesel piston head	CV joints	Truck hub	Tripot housing
Timing gears	Ring & pinion gears	Steering knuckles	Camshafts
Differential housing	Wheel spindle	Rocker arms	Shackle brackets
Steering housing	Tie rods	Suspension arms	Drive yokes
Brake components	U-bolt stop plates	I-beams	
Railroad			
Track plate	Brake caliper	Top caps	Mine car wheels
Axle holder	Wear shoes	Spring holder	Wheels
Shock absorbers	Brake blocks	Shoes	Engine parts
Machinery and Material Handling			
Power trans. gears	Conveyor link	Pump components	Conveyor link holder
Bearing block	Crankshafts	Chain sprockets	Conveyor chains
Cams	Wedges	Jackhammer housing	Mining wear parts
Wear pads	Pole line hardware	Sprockets	Dies
Rollers & Guides	Bull gears	Bevel gears	Grates
Spur gears			
Military			
Armor	Projectiles	Track shoes	Rocket bodies
Track guides	Engine rotors	Struts	Suspension

2.4. Aim of the work

From the literature review it is seen that austempered ductile iron as an engineering material has found increasing applications over the years since its discovery because of its excellent mechanical properties such as high strength, toughness, good wear resistance, good machinability and all that at low cost. The excellent mechanical properties of ADI material are due to its unique microstructure of ausferrite which consists of high carbon austenite and bainitic ferrite with graphite nodules dispersed in it. The austempered microstructure is a function of the austempering time and temperature and therefore achieving excellent mechanical properties depends on selection and control of proper austempering time, temperature and alloying additions.

Therefore, an attempt has been made in the present work to study the effect of austempering temperature, time and copper addition on the mechanical properties of austempered ductile iron such as tensile strength, % elongation, hardness and impact toughness by carrying out austempering treatment of ductile iron at 350°C, 300°C, and 250°C for 0.5hr, 1hr, 1.5hrs and 2hrs.

Chapter 3

Experimental Procedure

- Tensile Test
- Hardness Test
- Impact Test
- Heat Treatment
- Microstructure Study

3. Experimental Procedure

For this work two types of ductile irons: one containing copper about 0.5 wt% (Grade A) and the other without copper (Grade B), were collected from L & T, Kansbahal, Rourkela. The detailed chemical compositions of these materials are as per the table 3.1 and table 3.2.

Table 3.1 Chemical composition of Ductile irons (Grade A)

Elements	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Mg
%	3.54	2.33	0.24	0.013	0.030	0.02	0.14	0.001	0.51	0.044

Table 3.2 Chemical composition of Ductile irons (Grade B)

Elements	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Mg
%	3.53	2.11	0.19	0.013	0.033	0.02	0.45	0.001	0.01	0.043

3.1 Tensile Test

The specimens were prepared from the procured samples by carrying out machining operations such as grinding, turning and milling. This was done to obtain the required dimension (grip dia=20mm, gauge dia=14mm, gauge length=70mm, grip length=50 mm) for 100 tonne UTM testing.

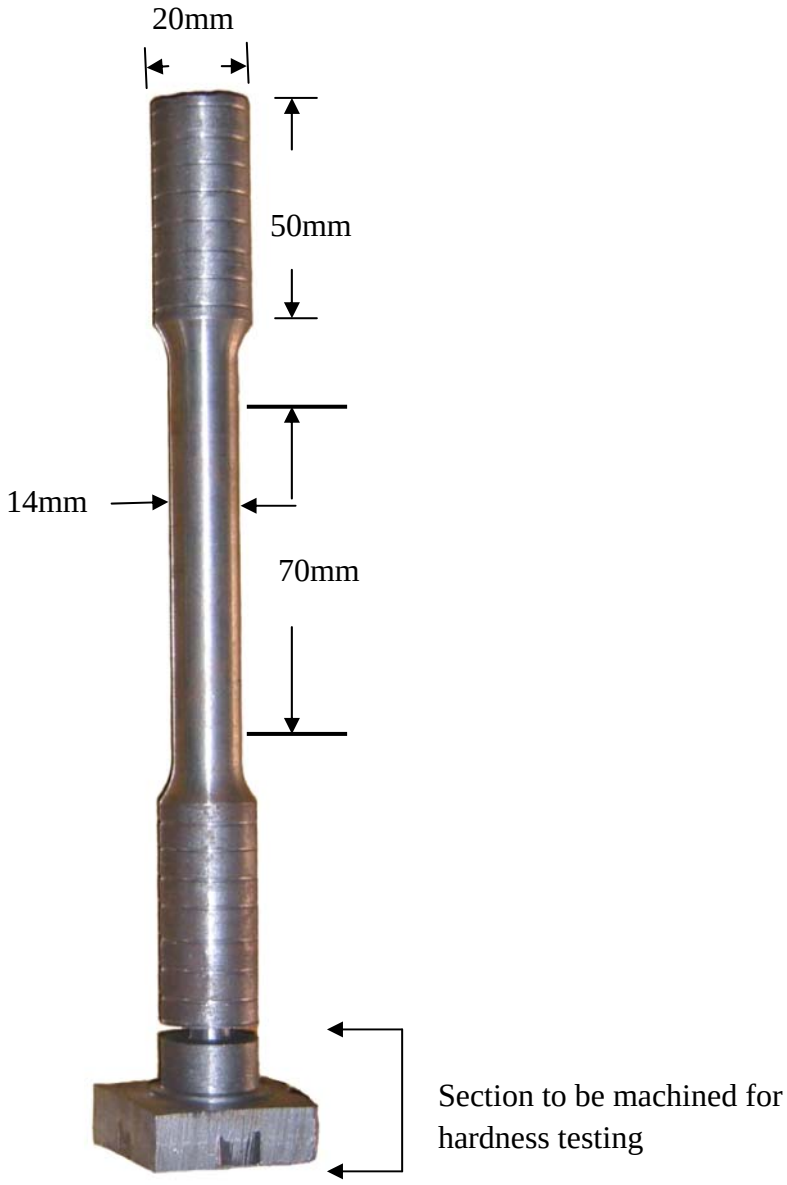


Figure 3.1 Tensile specimen specifications

The tensile test was carried out before and after the heat treatment

3.2. Hardness Test

The samples were taken for Brinell hardness test. The testing machine consists of a 10mm diameter steel ball indenter. A load of 3000 kgf was applied for 15 sec. The Brinell hardness number (BHN) is expressed as

$$BHN = \frac{P}{\frac{\pi d}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

Where, P = load applied (kgf)
D = Dia of the ball (mm)
d = Dia of indentation (mm)

3.3. Impact Test

The Charpy impact test, also known as the Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependent ductile-brittle transition. According to ASTM A370, EN 10045-1 and ISO 148 the standard specimen size for Charpy impact testing is 10mm×10mm×55mm. In this work following procedure was carried out for measurement of toughness.

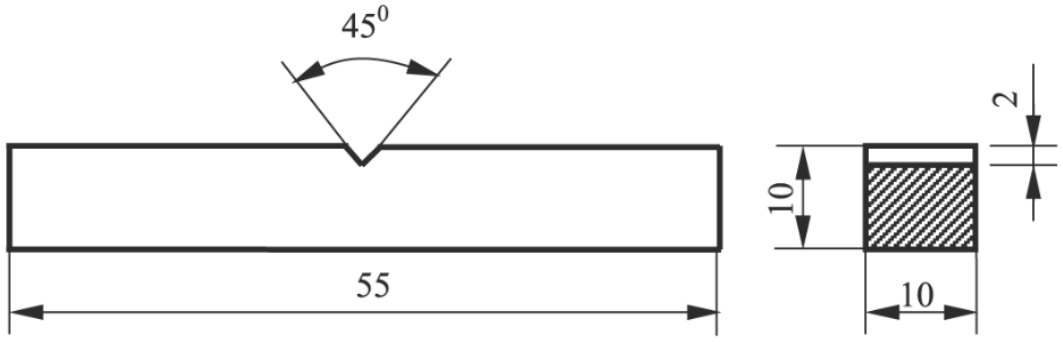


Figure 3.2 Dimensions for Charpy impact testing

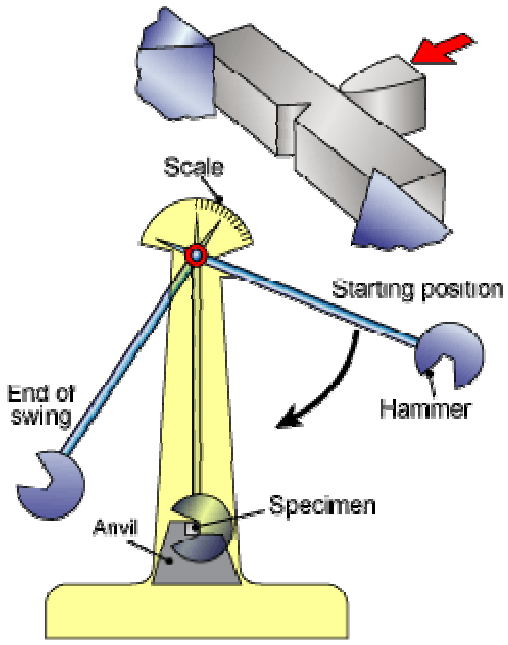


Figure 3.3 Arrangement for Charpy impact testing

- The Charpy specimen was placed horizontally across supports with the notch away from the hammer.

- The indicator pointer was slided to the left until it indicated the maximum energy range on the upper Charpy-Tension scale.

- The pendulum arm was raised to the right until it is firmly supported by the latching mechanism.

- The pendulum was released by pushing upon the release knob. The hammer dropped, striking the specimen, with a swing and the amount of energy absorbed by the test specimen to break was provided by the indicator with a direct reading of toughness of the specimen.

3.4. Heat Treatment

Nodular cast irons (or ductile, or spheroidal graphite iron) are primarily heat treated to create matrix microstructures and associated mechanical properties not readily obtained in the as-cast condition. As-cast matrix microstructures usually consist of ferrite or pearlite or combinations of both, depending on cast section size and/or alloy composition. The principal objective of the project is to carry out the heat treatment of SG cast Iron and then to compare the mechanical properties. The heat treatment comprises two stage processing: Austenitizing and Austempering

a) Required no. of specimens (for each observation at least 3 samples) were heated to the temperature of 910° C in laboratory atmosphere in a laboratory resistance furnace for 1 h so that the specimen got properly homogenized [23].
b) A salt bath was prepared by taking 50% $NaNO_3$ and 50 % KnO_3 salt mixture in a salt bath furnace. The objective behind using $NaNO_3$ and KNO_3 is though the individual melting points are high the mixture of these salts in the bath with 1:1 proportion form an eutectic mixture and this eutectic reaction brings down the melting point of the mixture to 225° C. The salt remains in the liquid state in the temp range of 225-550° C [24-26].
c) After the specimens were properly homogenized at 910° C these were taken out of the furnace and immediately put in the salt bath furnace where the containers with the salt mixture were kept at 350^0C, 300^0C and 250^0C.
d) In the salt bath the specimens were held for 0.5 hrs, 1 hr, 1.5 hrs and 2 hrs, as given in table 3.3. In this time the austenite gets converted to required microstructures. The objective behind choosing the maximum temperature of 350° C is that heat treating within this temperature will give lower bainitic ferrite which is acicular in structure so that the properties developed in the materials are excellent.
e) During transfer of the samples to the salt bath or cooling to room temperature, due to slight oxidation of the surface of cast iron, there is every possibility of scale formation on this surface. If the specimens are sent for testing with the scales in the surface then the hardness value will vary and the specimen will not also be gripped properly in the

machine. To avoid these difficulties the surface of the specimens were polished to remove the scales from the surface. After the scale removal the specimens were ready for the further experimentations.

Table 3.3 The Austempering Window

Austenitizing Temperature	Austempering Temperatures	Holding time in Salt Bath
910^0C	350^0C	0.5Hrs
		1.0Hrs
		1.5Hrs
		2.0Hrs
910^0C	300^0C	0.5Hrs
		1.0Hrs
		1.5Hrs
		2.0Hrs
910^0C	250^0C	0.5Hrs
		1.0Hrs
		1.5Hrs
		2.0Hrs

3.5. Microstructure Study

Preparation of cast iron specimens is difficult due to the need to properly retain the graphite phase [21]. The specimens were subjected to coarse grinding using motor driven emery belt. Coarse grinding is required to planarize the specimen and to reduce the damage created by sectioning. The planar grinding step is accomplished by decreasing the abrasive grit/ particle size sequentially to obtain surface finishes that are ready for polishing. The machine parameters, which effect the preparation of metallographic specimens, should be taken care of, for example grinding/polishing pressure, speed, and the direction of grinding/polishing. The other steps were rough polishing using abrasive papers of successively finer grades. In order to ensure that the previous rough grinding damage is removed when grinding by hand, the specimen should be

rotated 90 degrees and continually ground until all the scratches from the previous grinding direction are removed. If necessary the abrasive paper can be replaced with a newer paper to increase cutting rates. Then fine polishing was done in a cloth polishing mill using alumina powder as polishing agent. The purpose of final polishing is to remove only surface damage. It should not be used to remove any damage remaining from cutting and planar grinding. If the damage from these steps is not complete, the rough polishing step should be repeated. Finally the samples were etched for microstructure study. The purpose of etching is to optically enhance micro-structural features such as grain size and phase features. Etching selectively alters these micro-structural features based on composition, stress, or crystal structure. The most common technique for etching is selective chemical etching. Chemical etching selectively attacks specific micro-structural features. Here etchant used was nital (2% conc. Nitric acid in methanol solution) and washed thoroughly and dried. Then the microstructures were taken for different heat treated specimens using Scanning Electron Microscopy (SEM) with required magnifications [22].

Chapter 4

Results and Discussion

- Mechanical Properties
  - Tensile Test
  - Hardness Test
  - Impact Test
- Microstructural Observations

4. Results and Discussion

4.1. Mechanical Properties

4.1.1. Tensile Test

The mechanical properties of ductile cast iron in the as cast condition as obtained from the tensile test are given in the table 4.1.

Table 4.1 Tensile test results of as cast Ductile Iron samples

SAMPLES	T.S (MPa)	% Elongation
Without Cu	588	10.2
With Cu	732	7.14

As seen from the Table 4.1 copper addition results in a significant increase in the tensile strength of as cast Ductile Iron from 588 MPa to 732 MPa but the ductility decreases from 10.2% elongation to 7.14% elongation. This indicates that copper addition results in strengthening of as cast Ductile Iron probably due to promoting and refining the pearlitic phase in comparison to as cast (ferritic + pearlitic) condition.

The tension test results for the austempered ductile iron samples (without copper) are listed in the table 4.2.

Table 4.2 Mechanical properties of austempered samples (without Cu)

SL No.	Austempering window	Tensile Strength MPa	Elongation %
1	350^0C/0.50hrs	1080	2.212
2	350^0C/1.00hr	1040	2.663
3	350^0C/1.50hrs	970	2.724
4	350^0C/2.00hrs	953	2.498
5	300^0C/0.50hrs	1107	2.000
6	300^0C/1.00hr	1026	2.429
7	300^0C/1.50hrs	994	2.857
8	300^0C/2.00hrs	913	2.14
9	250^0C/0.50hrs	1204	1.000
10	250^0C/1.00hr	1202	1.286
11	250^0C/1.50hrs	1165	1.857
12	250^0C/2.00hrs	1061	1.857

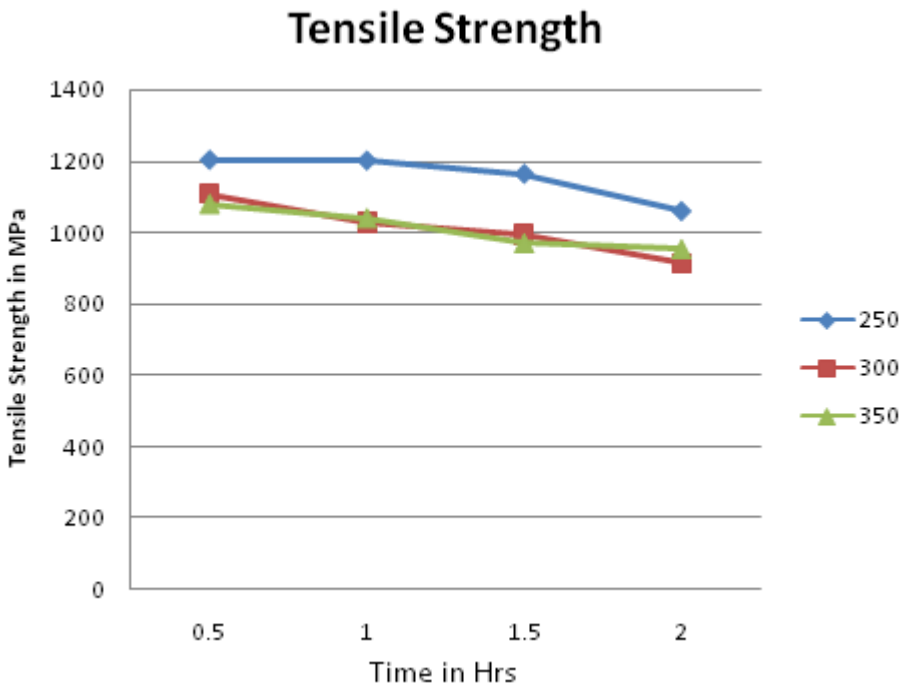


Figure 4.1 Effect of austempering time on tensile strength of Ductile Iron without Cu austempered at different temperatures

As seen in Figure 4.1 the tensile strength of ductile iron decreases with increasing austempering time. In the stage –I of isothermal transformation (figure 2.5) it is reported [14] that the amount of retained austenite increases with time. This increase in the amount of stabilized austenite in the samples could be reason for decrease in the tensile strength of ductile iron with increasing austempering time. Tensile strength increases with lower austempering temperatures and maximum strength is seen in the samples austempered at 250°C. It is reported [11] that austempering at lower temperatures leads to a higher carbon amount trapped in the bainitic α–phase and therefore increasing the tetragonality of bainitic α-phase lattice and lower volume fraction of austenite retained in the material, thus corroborating the results of higher tensile strength seen in samples austempered at lower temperatures.

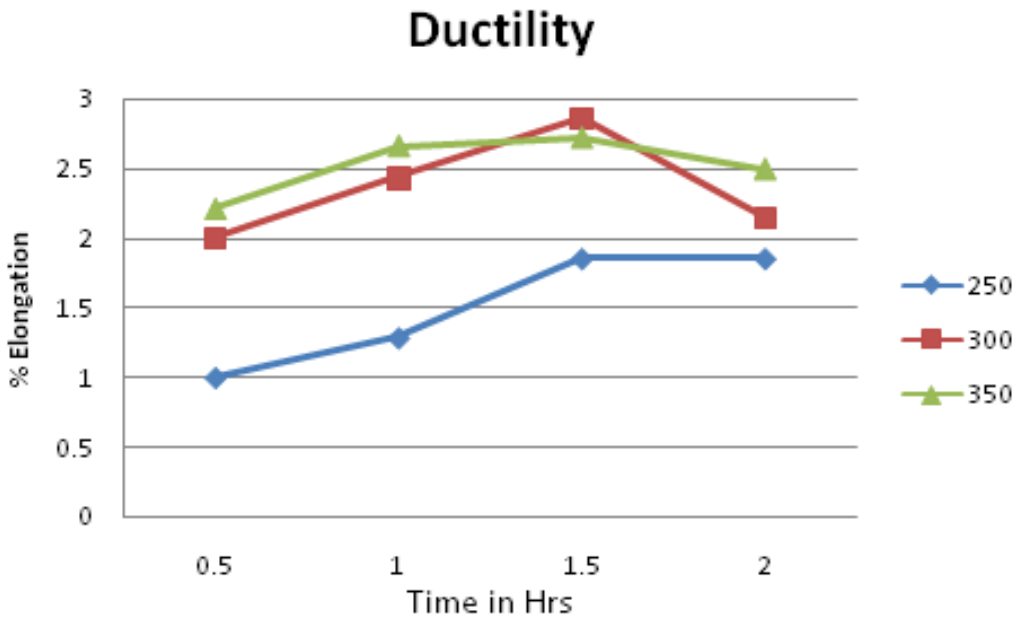


Figure 4.2 Effect of austempering time on Elongation of Ductile Iron without Cu austempered at different temperatures

From figure 4.2. it is seen that % Elongation of ADI samples increases with increasing austempering temperatures indicating the formation of less distorted (less c/a ratio) of bainitic α-phase and higher amount of retained austenite at higher temperatures [11]. The ductilty is found to increase with increasing austempering time upto 1.5 hours due to increase in the amount of retained austenite with austempering time and less martensite on subsequent cooling to room temperature. Beyond 1.5 hours a decrease in ductility is seen in some samples due to start of the Stage II of austempering reaction when retained austenite decomposes to bainitic ferrite and carbide [14].

The tension test results for the austempered ductile iron samples (with copper) are listed in the table 4.3.

Table 4.3 Mechanical properties of austempered samples (with Cu)

SL No.	Austempering window	Tensile Strength MPa	Elongation %
1	350^0C/0.50hrs	972	7.627
2	350^0C/1.00hr	968	8.095
3	350^0C/1.50hrs	959	8.128
4	350^0C/2.00hrs	955	8.076
5	300^0C/0.50hrs	979	7.543
6	300^0C/1.00hr	965	7.857
7	300^0C/1.50hrs	962	8.127
8	300^0C/2.00hrs	953	8.032
9	250^0C/0.50hrs	1027.5	7.215
10	250^0C/1.00hr	1021.4	7.483
11	250^0C/1.50hrs	995.8	7.811
12	250^0C/2.00hrs	998.6	7.805

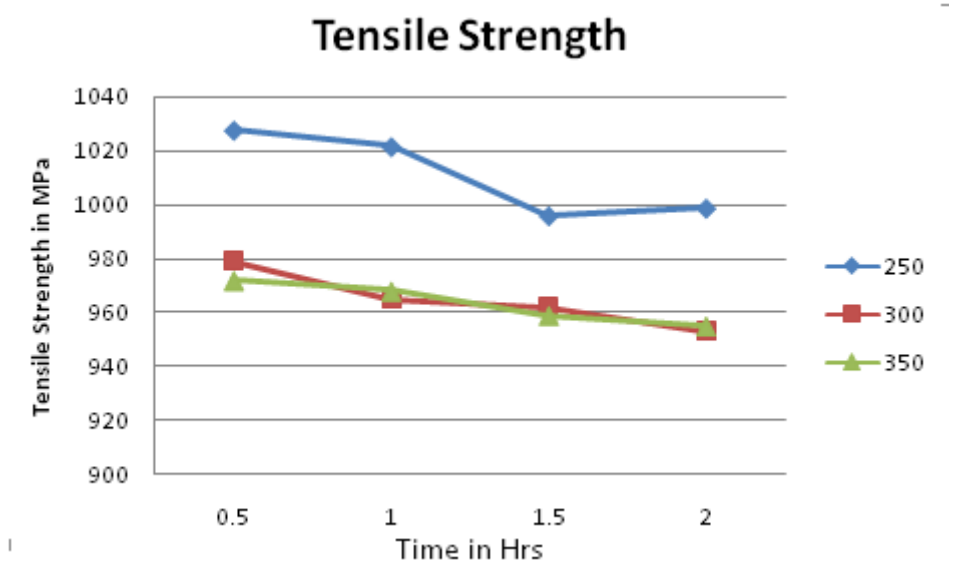


Figure 4.3 Effect of austempering time on tensile strength of Ductile Iron with Cu austempered at different temperatures

As seen in figure 4.3 the tensile strength of austempered ductile iron samples with Cu shows the similar trend as in case of ductile irons without copper additions i.e. it decreases with increasing austempering time due to increasing amount of stabilized austenite in the samples. Tensile strength also increases with lower austempering temperatures due to formation of acicular bainitic ferrite and maximum strength is seen in samples austempered at 250°C. The tensile strength of austempered ductile iron samples with Cu is less in comparison to plain ADI. It has been reported that copper stabilizes the austenite during austempering [27] thereby leading to a product having lower tensile strength compared to plain ADI.

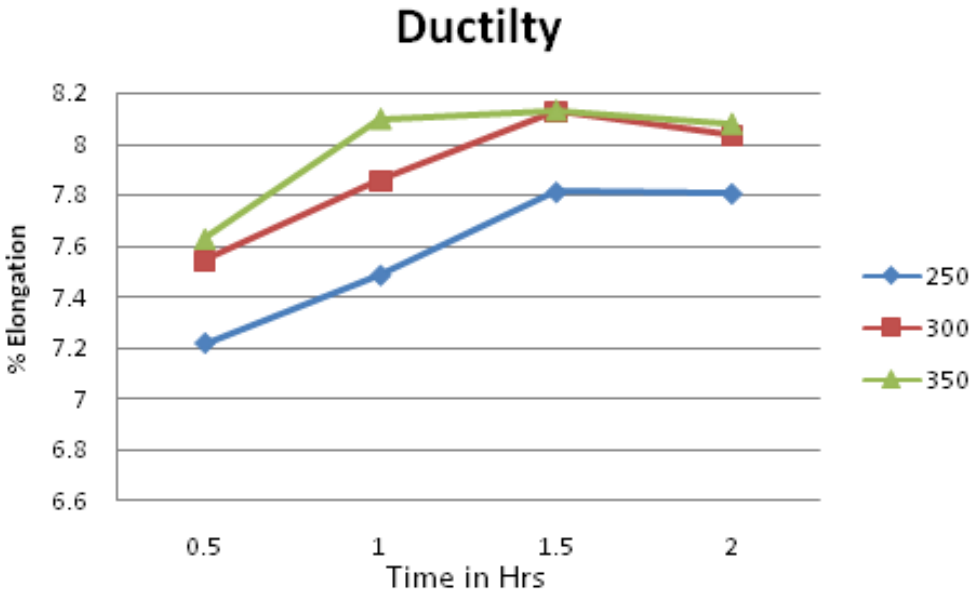


Figure 4.4 Effect of austempering time on Elongation of Ductile iron with Cu austempered at different temperatures

% Elongation of copper alloyed ADI is more in comparison to plain ADI. The elongation is found to increase with increasing austempering tempareture in a same fasion as that of ADI without copper additions and also increases with austempering time upto 1.5 hours.

During austempering copper probably increases the amount of bainitic α-phase and stabilized austenite mixture in the samples and decreases the amount of martensite on subsequent cooling to room temperature.

4.1.2. Hardness Test

The hardness values obtained from Brinell hardness tests are as follows:

The as received sample (without Cu) had the hardness of 162 BHN.

After austempering the hardness results obtained are listed in Table 4.4.

Table 4.4 Hardness of ADI without copper.

Austempering window		Hardness
Temp (°C)	Time (Hr)	BHN (10 mm, 3000 Kgf)
350	0.5	287
	1	273
	1.5	258
	2	245
300	0.5	292
	1	274
	1.5	262
	2	248
250	0.5	322
	1	308
	1.5	296
	2	271

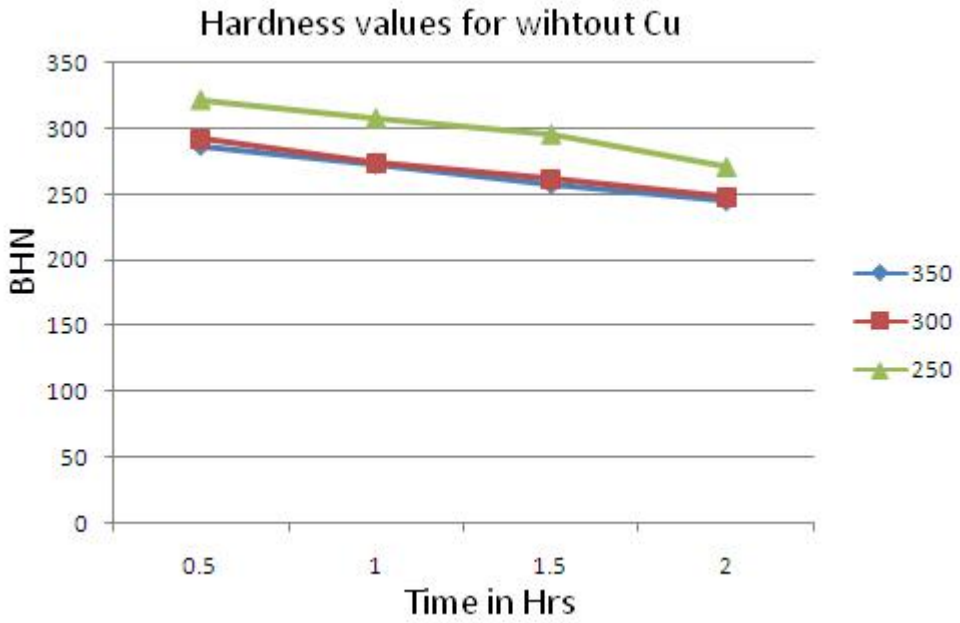


Figure 4.5 Effect of austempering time on Hardness of Ductile Iron without Cu austempered at different temperatures

The as received samples with copper had the hardness 187 BHN

After austempering the results obtained are listed in Table 4.5.

Table 4.5 Hardness of ADI with copper.

Austempering window		Hardness
Temp (°C)	Time	BHN (10 mm, 3000 Kgf)
350	0.5	269
	1	257
	1.5	243
	2	232
300	0.5	277
	1	256
	1.5	245
	2	231
250	0.5	309
	1	290
	1.5	278
	2	253

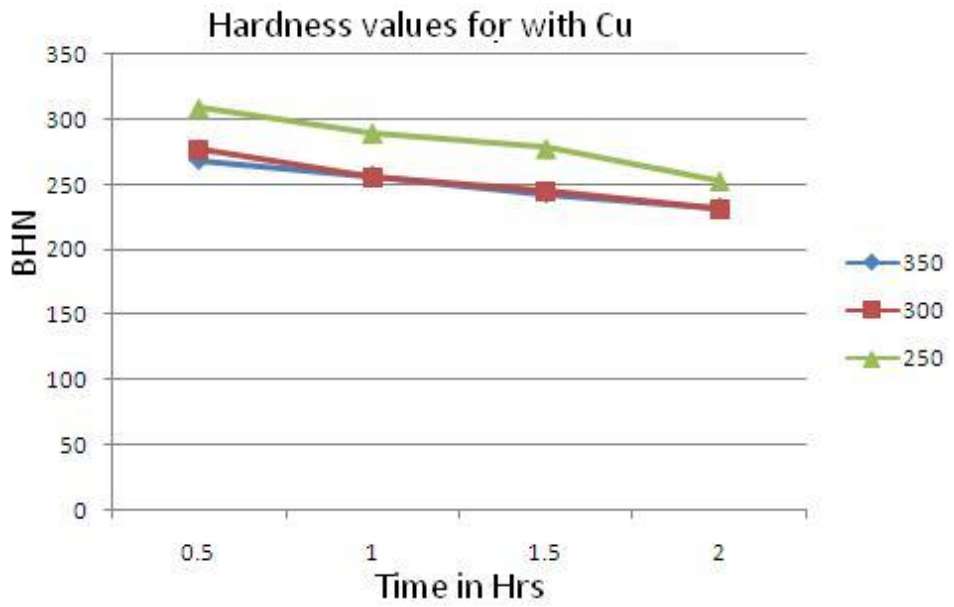


Figure 4.6 Effect of austempering time on Hardness of Ductile Iron with Cu austempered at different temperatures.

From the figures 4.5 and 4.6 it is evident that the hardness value of ADI increases during short times of austempering as during the subsequent cooling from austempering temperature to room temperature the formation of martensite cannot be prevented. As austempering time increases the carbon content of the austenite increases resulting in a decrease in M_s and M_f temperatures [Figure 2.5]. With somewhat longer austempering time the amount of retained austenite increases which results in decrease in hardness. Copper alloyed ADI samples exhibit lower hardness compared to plain ADI samples.

4.1.3 Impact Test

The variation of toughness with austempering time and temperature for austempered ductile iron samples without Cu are as shown in the table 4.6.

The as received sample of ductile iron without copper had the toughness (notched Charpy sample) value of 16J.

Table4.6 Toughness values for ADI without Cu.

Austempering window		Toughness values
Temp(°C)	Time (Hr)	Impact Energy(J)
350	0.5	13
	1	16
	1.5	20
	2	24
300	0.5	13
	1	15
	1.5	18
	2	20
250	0.5	12
	1	13
	1.5	17
	2	18

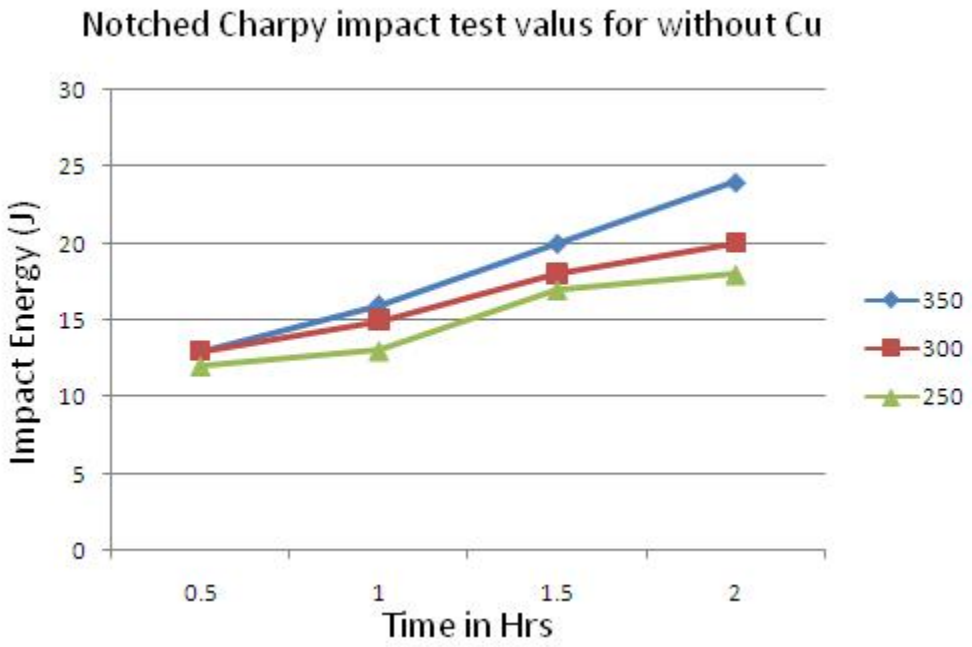


Figure 4.7 Effect of austempering time on Impact Toughness of Ductile Iron without Cu austempered at different temperatures.

The toughness values for notched samples were found to increase with increasing austempering time and increasing austempering temperatures due to the increase in ductility seen in such samples.

The variation of toughness with austempering time and temperature for austempered ductile iron samples with Cu are as shown in the table 4.7.

The as received sample of ductile iron with copper had the toughness (notched Charpy sample) value of 10 J.

Table 4.7 Toughness values for ADI with Cu.

Austempering window		Toughness values
Temp(°C)	Time (Hr)	Impact Energy(J)
350	0.5	24
	1	37
	1.5	40
	2	45
300	0.5	22
	1	34
	1.5	38
	2	41
250	0.5	21
	1	31
	1.5	35
	2	37

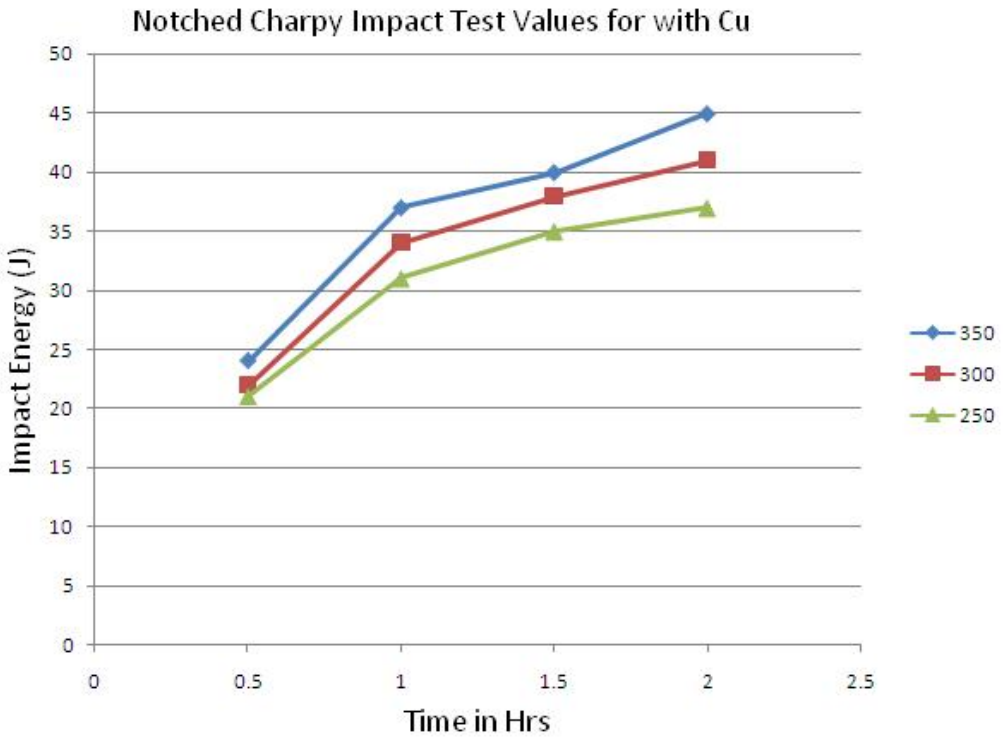
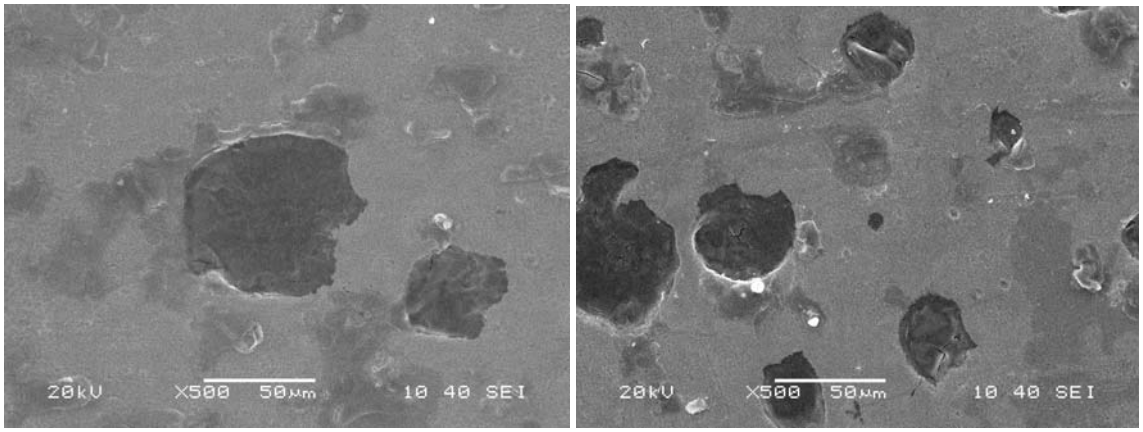


Figure 4.8 Effect of austempering time on Impact Toughness of Ductile Iron with Cu austempered at different temperatures.

The toughness values for notched ADI samples with copper similarly increased with increasing austempering time and higher austempering temperatures as in plain ADI samples because of greater ductility of the samples austempered for longer times and at higher temperatures. Copper alloyed ADI samples exhibited higher toughness values compared to plain ADI because of the effect of copper in stabilizing the austenite during austempering resulting in higher ductility [27].

4.2. Microstructural observations

The microstructures of ductile iron samples with and without copper austempered at 350°C were studied under scanning electron microscope with 550x magnification.



(a) (b)

Figure 4.9 SEM microstructures of ADI austempered at 350°C for 1.5 hrs (a) without copper (b) with copper.

As seen in Figure 4.9 the heat-treated microstructures of both materials consist of graphite nodules of different sizes in the matrix phase. From the microstructures it was seen that copper addition does not cause any observable change to the austempered microstructure of plain ADI. In some cases the copper is associated with the graphite nodules, but not necessarily as a thin film.

Chapter 5

Conclusions

5. Conclusions

From the study on the effect of austempering temperature, time and copper addition on the mechanical properties of austempered ductile iron the following conclusions could be drawn

1. Austempering significantly enhances the tensile strength of Ductile Iron with and without copper additions and higher tensile strength was obtained in samples austempered at lower temperatures of 250°C.

2. Ductility of Austempered Ductile Iron was found to increase with increasing austempering time and maximum ductility was seen in samples austempered up to 1.5 hours.

3. Addition of copper significantly increases the ductility of Austempered Ductile Iron with a slight decrease in tensile strength.

4. Hardness of both the plain ADI and copper alloyed ADI samples were found to increase with decreasing austempering temperature and time.

5. Toughness of ADI increases with increasing time and temperature of austempering treatment and was significantly higher in case of ADI samples with copper.

Chapter 6

Future Work

6. Future work

Austempered ductile iron has found enormous applications in recent years due to its high strength and hardness, with good toughness. It has started to replace steel in some structural and engineering applications. More work is needed to improve the properties like corrosion resistance, relative abrasive resistance and hardenability of ductile iron through studies on the effect of different alloying elements and heat treatment processes on the ductile iron.

References

References

[1] Hughes I.C.H, "Austempered Ductile Irons - Their Properties & Significance", Materials & Design, Vol-6, No-3, 1985, 124-126.

[2] W.F. Smith, "Structure and Properties of Engineering Alloys", second ed. Mc Graw-Hill, 1993.

[3] Labreeque C & Gagne M. "Reviewed of Ductile Iron: Fifty years of Continuous Development", Canadian Metallurgical Quarterly, 37, 5, 1998 343-378.

[4] Singh V, "Physical Metallurgy", Standard Publishers Distributors, 1999.

[5] Mullin J.D, "Ductile iron data for design engineers", Rio tinto iron & titanium inc., Montreal, Quebec, Canada, 1990.

[6] Rajan T.V, Sharma C.P, Sharma A, "Heat treatments-Principles and techniques", PHI, New Delhi, 2006.

[7] Davis J.R& associates, "Cast iron", ASM Society Hand book, 1996.

[8] Kim Yoon-Jun, Shin Hochoel, "Investigation into mechanical properties of austempered ductile cast iron (ADI) in accordance with austempering temperature", Materials Letters, Vol. 62, 2006, 357-360.

[9] "Austempered ductile iron", http://www.aditreatments.com.

[10] Keough J. R, Hayrynen K. L, "Austempered cast irons", Applied Process, Inc., Livonia, Michigan, 2004.

[11] Kustuv A, Taran Y, Uzlov J, Krimmel A, Evsyukov M, "Formation of bainite in ductile iron", Materials Science and Engineering, A 273-275, 1999, 480-484.

[12] Taran Y.N, Uzlov K.I, Kustuv, Bainitic reaction kinetics in austempered ductile iron, A.Y, J Phys. (Fr.) IV 7, 1997, C 5-429.

[13] P.W. Shelton, A.A.Bonner, "The effect of copper addition to the mechanical properties of austempered ductile iron (ADI)", Material Processing Technology, 173, 2006, 269-274.

[14] Olivera Eric, Milan Jovanovic, Leposava S, Dragan Rajnovic, Slavica Zec, "The austempering study of alloyed ductile iron", Materials and Design, 27, 2006, 617-622.

[15] Advanced cast products, http://www.advancedcast.com/adi-advantages.htm.

[16] http://www.durhamfoundry.com/austempered_ductile_iron.htm.

[17] http://www.wmlee.co.uk.

[18] Harding R. 2nd International conference on austempered ductile ASME gear research institute. Ann Arbor (MI): ASME Gear Research Institute; 1986, 39-54.

[19] Kovacs B. Trans AFS 1990; 103:38.

[20] Mullin JD. "The market of ductile iron casting is still growing", Sorelmetal review, 83, 2006.

[21] Radzikowska J.M, "Effect of specimen preparation on evaluation of cast iron microstructure", Materials characterization, 54, 2005, 287-304.

[22] Donald C. Zipperian, "Metallographic Specimen Preparation Basics", Pace technology, 2001.

[23] Hafiz M, "Mechanical properties of SG iron subjected to variable and isothermal Austempering temperatures heat treatment", Materials science and engineering, A340, 2003, 1-7.

[24] Dubal G.P, “Salt bath quenching”, Advanced materials & processes, 1999.

[25] Foreman R.W, “New developments in salt bath quenching”, Industrial heating, 1993 Vol. 60 (3), 41-47.

[26] Abdel-Hakim H.A., Attia A.A., Baraka A.M, “Dissolution susceptibility of oxide species formed on mild steel during its oxidation in molten KNO_3-$NaNO_3$ eutectic mixture”, Journal of Materials Engineering and performance, Vol. 11(3) 2002, 301-305.

[27] Silman G. I, Kamynin V.V, Goncharov V. V, “On the mechanism of copper effect on the structure formation in cast iron”, Material Science and Heat Treatment, vol. 49, 2007, 7-8.